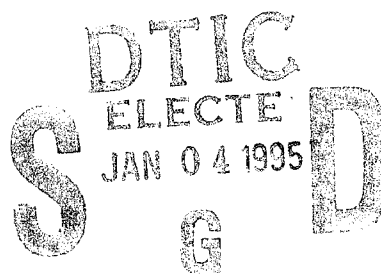


Subvisual Cirrus: What It Is and Where You Find It

1 November 1994



Prepared by

D. K. LYNCH
Space and Environment Technology Center
Technology Operations

Prepared for

SPACE AND MISSILE SYSTEMS CENTER
AIR FORCE MATERIEL COMMAND
2430 E. El Segundo Boulevard
Los Angeles Air Force Base, CA 90245

Engineering and Technology Group


APPROVED FOR PUBLIC RELEASE;
DISTRIBUTION UNLIMITED

19941229 002

This report was submitted by The Aerospace Corporation, El Segundo, CA 90245-4691, under Contract No. F04701-88-C-0089 with the Space and Missile Systems Center, 2430 E. El Segundo Blvd., Suite 6037, Los Angeles AFB, CA 90245-4687. It was reviewed and approved for The Aerospace Corporation by A. B. Christensen Principal Director, Space and Environment Technology Center. Major Leslie Belsma was the project officer.

This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.


LESLIE BELSMA, MAJ, USAF
Project Officer

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE 1 November 1994		3. REPORT TYPE AND DATES COVERED
4. TITLE AND SUBTITLE Subvisual Cirrus: What It Is and Where You Find It			5. FUNDING NUMBERS F04701-88-C-0089	
6. AUTHOR(S) Lynch, David K.				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) The Aerospace Corporation Technology Operations El Segundo, CA 90245-4691			8. PERFORMING ORGANIZATION REPORT NUMBER TR-93(3308)-1	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Space and Missile Systems Center Air Force Materiel Command 2430 E. El Segundo Blvd. Los Angeles Air Force Base, CA 90245			10. SPONSORING/MONITORING AGENCY REPORT NUMBER SMC-TR-94-46	
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) Extremely low column density ice clouds (subvisual cirrus) have significant impacts on passive IR remote sensing of both the atmosphere and the Earth. In this report I review the physical properties of subvisual cirrus and discuss their detection and global distribution.				
14. SUBJECT TERMS Cirrus Subvisual Climate Visibility Clouds			15. NUMBER OF PAGES 14	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT	

Subvisual Cirrus:
What it is and where you find it.

David K. Lynch

The Aerospace Corp. M2-266
P.O. Box 92957
Los Angeles, CA 90009
(310) 336-6686
(310) 336-1636 FAX
DIRAC2::LYNCH
(Internet)

Accession For	
NTIS CRA&I	<input checked="" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By	
Distribution /	
Availability Codes	
Dist	Avail and/or Special
A-1	

ABSTRACT

Extremely low column density ice clouds (subvisual cirrus) have significant impacts on passive IR remote sensing of both the atmosphere and the Earth. In this paper I review the physical properties of subvisual cirrus and discuss their detection and global distribution.

1. INTRODUCTION

High, thin, nearly invisible cirrus has been known for years. Uthe¹, Barnes^{2,3}, Heymsfield⁴ describes observations over Kwajalein where pilots and lidars could clearly see the cloud but DMSP and ground observers could not. Such clouds have come to be known as subvisual cirrus (SVC). Subvisual cirrus found in the tropics is sometimes called high altitude tropical (HAT) cirrus⁵. Sassen^{6,7} and his collaborators present valuable new results on SVC. Additional important information about SVC can be found in Flatau⁸, Liou⁹, Takano¹⁰, Platt¹¹, Hutchinson^{12,13}, Schmidt¹⁴ and Dalcher¹⁵.

The term "cirrus" refers to a principal cloud type with morphologically distinct features. Cirrus is defined as detached clouds that appear as thin (without self-shadowing), white, fibrous tufts usually showing delicate filaments, often with considerable vertical extent. Cirrus is composed of ice crystals and its optical morphology is a result of glaciation, ice crystal microphysics and the interaction of falling crystals with atmospheric winds.

Most people correctly equate "cirrus" to "ice crystal cloud", but not all ice crystal clouds are cirrus. In the winter, most polar continental stratoform clouds are made of ice (or are mixed phase) yet they have no visual resemblance whatever to cirrus. The same is true for ice fogs ("diamond

dust"). In this paper subvisual cirrus will mean any ice cloud whose optical depth is small (< 0.1 in the visible).

Subvisual cirrus is of interest for a number of reasons. Being nearly transparent, SVC is difficult if not impossible to detect with automated cloud detection algorithms whose optical depth limit is nominally 0.1 in the visible^{16,17}. Cirrus is also thought to be a major factor in controlling the earth's radiation budget. Finally, small ice particles (the kind thought to comprise much SVC) are difficult to detect with *in situ* probes and thus even direct attempts to sample such clouds are difficult.

The goals of this paper are to review SVC and to suggest that they are a common and distinct subclass of cirrus clouds characterized by a relatively narrow range of physical properties.

2. HISTORY AND CONCEPT OF SUBVISUAL CIRRUS

The US Army's Kwajalein Missile Range (KMR now known as USAKA - United States Army Kwajalein Atoll) in the Marshall Islands has played an important role in identifying and studying SVC. Kwajalein is located in the western Pacific ocean near 167° W, 9° N and its weather is dominated by the intertropical convergence zone (ITCZ) where the tropopause can be high, sometimes reaching 60,000 ft. During 1986 the author was part of team using NASA's Learjet to make various measurements of cirrus clouds, IR backgrounds and Halley's comet in Kwajalein¹⁸. During our daytime flights, the aircraft routinely reached 45,000 ft pressure altitude (about 47,000 ft MSL) and cirrus was present above us most of the time between March and September. In many cases the 22° halo was present and on at least one occasion a parhelion was observed. The former observation tells us that the crystals had well developed 60° prism faces and the latter tells us that large ($> 30 \mu\text{m}$ faces), oriented plate crystals were present¹⁹.

Kwajalein Chief Meteorologist (in 1986) Don Thornley tells the story of how post-WW II high altitude aircraft (for the time) flying at 35,000 ft reported a thin layer of cirrus "just above us". As planes got better and the ceilings raised, the pilots reported the same thin cirrus just above them at 40,000 ft, then later 45,000 and still later at 50,000 ft. The repeated anecdotes of cirrus that was always just out of the aircraft's altitude ceiling lead to the term *cirrus evadus*. Sounding rockets verified that there was usually a thin layer of cirrus at the tropopause (55,000 ft typically) when the ITCZ was over Kwajalein. This layer was as little as 0.5 km thick and was rarely if ever reported by ground observers.

All but one of the handful of studies of SVC have taken place at Kwajalein. It is possible that the conclusions based upon such data may be only valid for the eastern Pacific and not

representative of other places in the world.

3. "VISUAL" ASPECTS OF SUBVISUAL CIRRUS

The term "subvisual" suggests that a human observer cannot detect the clouds. In general this is an apt description, although solar scattering angle, cloud structure and line-of-sight viewing angle also play important roles. Clouds whose contrast away from the sun is below the visual threshold brightness can be seen without difficulty when viewed close to the sun. This is a result of the well-known forward scattering properties of particles whose size parameters are large (> 10) regardless of their shape. Owing to the absence of any visible structure for the eye to seize upon, a completely uniform cover of thin cirrus might pass unnoticed even to a trained observer even though the cloud's brightness exceeded the visible threshold. Even without some density structure, some uniform cirrus makes its presence known only by showing halos, usually parhelia or the 22° halo. Very thin (but still visible) cirrus is sometimes called "blue cirrus" because it does not scatter enough white light to appreciably alter the much brighter blue background skylight. Finally, SVC is usually only about 1 km thick but may be many km wide. Therefore a vertical viewing angle will pass through far less material than will one which is nearly horizontal. This explains why pilots can often see thin cirrus as they fly towards or through a thin cloud but ground observers cannot. It also explain why thin clouds are always more visible near the horizon than overhead.

Cirrus whose visible optical depth is less than about 0.1 could well be missed by both ground and satellite observations. Sassen^{6,7} suggest that the boundary between subvisual cirrus and visible cirrus is about $\tau = 0.03$. This compares favorably with the findings of Platt¹¹ who find $\tau = 0.06$ for visible but hazy cirrus.

4. GLOBAL DISTRIBUTION OF SUBVISUAL CIRRUS

The global distribution of subvisual cirrus is virtually unknown. Cirrus climatologies, however, have been done and they reveal that cirrus displays mesoscale organization^{20,21,22}. To the extent that SVC is correlated with ordinary cirrus, we can use the latter as a guide (Table 1 lists cirrus global frequency distribution studies). Ordinary cirrus is concentrated near the equator (ITCZ) where deep convection occurs, and at midlatitudes, where it is associated with frontal boundaries. The global frequency over land is about 23%. The zonal frequency varies from between 5 and 40%. Because most studies do not detect subvisual cirrus, the numbers quoted above must be viewed as lower limits if applied to SVC. There is some evidence that subvisual cirrus may be much more common than previously supposed and may be ever-present in some parts of the world. This notion is reinforced by LIDAR observations that often show cirrus when

no other probe detects anything. Quoting Barnes³ "We found that thin cirrus was present almost all of the time at Kwajalein." Owing to the present limitations of visual observers and cloud detection algorithms, it is possible that high, thin cold cirrus could have been present during all of the studies listed in Table 1 without being detected.

TABLE 1 - CIRRUS GLOBAL DISTRIBUTION STUDIES

<u>STUDY</u>	<u>DATA</u>
Barton ²³	NIMBUS-5
Woodbury ²⁴	SAGE/AEM
Woodbury ²⁵	SAGE/AEM
Chiou et al. (1990) ²⁶	SAGE/AEM
Henderson-Sellers ²⁷	Gound based/METEOSAT
Prabhakara ²⁸	NIMBUS-4
Menzel and Wylie ²⁹	GOES/VAS
Menzel and Wylie ³⁰	HIRS/NOAA-10,11
Rossow and Schiffer ³¹	ISCCP
Warren ^{32,33}	Surface Obs
Wylie ³⁴	GOES/VAS
Wylie ³⁵	GOES/VAS

5. MICROPHYSICAL PROPERTIES OF SUBVISUAL CIRRUS

The most complete observations of subvisual cirrus are given by Sassen^{6,7}, Heymsfield⁴ and Barnes^{2,3}. While the first two reports were in fairly good agreement with each other, the latter reported measurements of tropical SVC showing that two types exist: those with particle radii less than about 10 μm (in agreement with later work) and those with particles larger than about 100 μm . While one might expect SVC to have almost any range of particles sizes, Barnes demonstrated that a large fraction of tropical SVC is composed of small particles. The microphysical aspects of their work is summarized in Table 2 and 3 along with related properties of all cirrus clouds reviewed by Dowling³⁶. To the extent that we can believe any trend suggested by only two studies, we can say that subvisual cirrus is:

TABLE 2 MEASURED PROPERTIES OF SUBVISUAL CIRRUS

location	Kwajalein	Wausau, WI	Kwajalein	Kwajalein	Regular Cirrus
long, lat.	167.7 E, 8.8 N	89.63 W, 44.93 N	167.7 E, 8.8 N	167.7 E, 8.8 N	
time-of-year	Dec 17, 1973	Oct 21, 1986	various	various	
time-of-day	9-17 local	7:45 - 9 am local	various	various	
topography	Pacific atoll	mid cont. grassland	Pacific atoll	Pacific atoll	
climatology	ITCZ, trades	jetstream, frontal	ITCZ, trades	ITCZ, trades	
top-base (km)	16.7 - 16.2	12 - 13, broken			9 (4 - 20)
thickness (km)	0.5	~10			1.5 (0.1 - 8)
trop height (km)	16.7	12.8			
instrumentation	L, A, S, V	L, C, S, V	L, V	L, V	
pressure (mb)	108 - 99				
temperature (C)	-83	-65 - -62			
IWC (g m ⁻³)	1 x 10 ⁻⁴	2 x 10 ⁻⁴	10 ⁻⁹ - 10 ⁻⁸	(10 ⁻⁴ - 10 ⁻⁵)	2.5 x 10 ⁻² (10 ⁻⁴ - 1.2)
crystal type	trig. plts/col (~1:1)	~spherical	mean 2	~500	250 (1-8000)
crystal size (μm)	5 - 50 (mean 5)	mean 25	10 ³ - 10 ⁴	< 1	(3x10 ⁴) (10 ⁻¹ - 10 ⁷)
num dens (m ⁻³)	5 x 10 ⁴	2.5 x 10 ⁴	[4]	[4]	[1]
reference	[2]	[3]			
instrumentation:	A - aircraft C - camera L - lidar P - particle sampler S - sonde V - visual observer				
references:	[1] Dowling and Radke (1990) [2] Heymsfield (1986) [3] Sassen, Griffin and Dodd (1989) [4] Barnes (1982)				

There is clearly a strong observational bias towards cirrus over Kwajalein. Dowling and Radke (1990) conclude that "The measured ranges displayed by the various properties show that cirrus clouds [*not subvisual cirrus*] defy comfortable characterization by any single set of numbers." Sassen and Cho (1993) note that "Climatologically, subvisual/thin cirrus appear to be higher, cooler, more strongly depolarizing than previously reported midlatitude cirrus, although similar $k/2\eta$ that decrease with height and temperature are found." (k = backscatter-to-extinction ratio, η = multiple scattering correlation factor)

1. almost always found at or near the tropopause, at least at low and midlatitudes.
2. composed of small ($< 10 \mu\text{m}$ radius), nonspherical ice particles
3. optically thin
4. small vertical extent

Items 3 and 4 above suggest that SVC is virtually isothermal.

We suggest that the observed range of properties of subvisual cirrus is sufficiently restricted to identify them as a well-defined subclass of ordinary cirrus. This is not to say that subvisual cirrus cannot be found well below the tropopause or with large crystals. Indeed, thin, midlevel cirrus, especially in a low humidity region where the particles were sublimating could well be subvisual. Our point is that thin, virtually invisible cirrus clouds routinely form and endure near the tropopause and have a number of consistent microphysical properties.

The greatest source of uncertainty in Table 2 and 3 involves the ice-water content, crystal type, size and number density. The measured IWC depends on correctly counting the particles. Yet both studies recognized that they were unable to count particles smaller than $D = 10$, where D is the largest dimension of the crystal. Most particle size distributions including those of Heymsfield³⁷ are heavily weighted numerically towards small particles, the slope of the logarithmic distribution being about -3.8 for the coldest particles.

6. MODELS OF SUBVISUAL CIRRUS

Any future model of subvisual cirrus must be consistent with the findings above. Given the properties listed in Tables 2 and 3, the simplest possible yet physically-meaningful subvisual cirrus cloud is one represented by an isothermal layer of (usually) small particles at a single temperature and height. The role of small particles has been discussed by Platt³⁸ and Takano¹⁰.

Previous models have been produced by several groups. Shettle^{39,40} implements a subvisual cirrus model in LOWTRAN7 in which the particles are treated as spheres. Liou⁹ developed the SUBVIS code which was a LOWTRAN7-compatible cloud subroutine. They can also model the particles as hexagonal crystals for certain ranges of size parameter. The model explicitly treats thin cirrus clouds although their particle size distributions may have included larger particles than may be appropriate for subvisual cirrus.

7. DETECTION OF SUBVISUAL CIRRUS

The ability to detect SVC is clearly an important goal. Since neither visual observer nor existing passive satellite systems can reliably find thin cirrus, we must first learn how to find and

characterize subvisual cirrus by any means, and then apply the results to satellite systems.

A. In Situ Measurements (Aircraft) The most reliable method for detecting cirrus clouds is to fly through them, sample the particles and verify that they are made of ice. This method also allows the determination of particle size, shape, number density and cloud thickness. Alternatively, balloons can be used to sample clouds but this method is less reliable because the trajectory of the balloon cannot be controlled. Another direct sampling technique is to use dropsondes. These are instrumentation packages that are parachuted into the suspected cloud area from an aircraft. Both methods can measure all the state variables as well as sample the cloud particles. The advantage of *in situ* sampling is that you know what kind of particles you are dealing with. The disadvantage is that only a minute fraction of the cloud can be sampled and this involves gathering data over a period of time during which the cloud can change.

B. Lidars. The most flexible method for remotely sampling the cloud is to use a lidar⁴¹. Dual polarization lidars give depolarization information which can usually distinguish ice particles from water drops. Lidars can operate at any angle with respect to the zenith and both zenith and non-zenith observations are valuable in characterizing the particles' properties. Lidar directly measures the volume backscatter coefficient. Existing laboratory measurements and model calculations can then be used to compute the backscatter-to-extinction ratio, which then is used to calculate the transmission of the cloud. Ideally, two lidars should be used; one at visible wavelengths and the other in the 10 μm atmospheric window. This allows both a range of particles sizes to be more completely measured and also provides backscatter information to be obtained near the infrared wavelength region of interest. In order to calibrate the lidar, the temperature, pressure, humidity, etc must be known along the optical path. These data are normally obtained using sondes and therefore balloons and radar tracking equipment must also be available. The main advantage of a lidar is that backscatter as a function of height AGL can be directly measured and can therefore be directly related to the sonde data for inversion. Lidar can also sample a large volume of the cloud quickly so that ranges in the scattering properties of the cloud can be specified.

C. Passive Infrared spectroscopy/photometry from the ground^{42,43,44,45} or space^{35,46,47} used in conjunction with cloud particle models can be used to detect cirrus clouds. Using models of atmospheric transmission and the measured state variables of the atmosphere, a transmission of the cloud can be calculated. The advantage of a passive system is its simplicity. The disadvantage is that no height information about the cloud is directly available and the transmission depends on large amounts of modelling. Furthermore, the presence of low-tropospheric and stratospheric particles unrelated to the cirrus cannot be determined or accounted for. Such aerosols can seriously confuse the inversion of data to derive cirrus cloud transmission, especially when the cirrus is thin or subvisual.

8. SUMMARY AND CONCLUSION

Cirrus cloud optical thicknesses have an enormous range and there is no *a priori* reason to believe that there is some physical process bounding them. There is, however, some evidence to suggest that a common and poorly observed subclass of cirrus exist near the tropopause whose visible optical depths are less than about 0.1. This so-called subvisual cirrus (SVC) has significant impact on many aspects of remote sensing and atmospheric physics, although greater study is needed. Table 3 summarizes the properties of these clouds.

TABLE 3. SUGGESTED BASELINE SUBVISUAL CIRRUS PROPERTIES

composition	nonspherical ice particles
particle size (long dimension)	< 50 μm
particle shape	plates, columns, bullets, clusters
number density	< $5 \times 10^4 \text{ m}^{-3}$
thickness (Δz)	< 1 km
height	12-18 km (at or near tropopause)
horizontal size	mesoscale (20 - 2000 km)
temperature	-50 C
temperature range	nearly isothermal
optical thickness (τ)	< 0.05 in visible
depolarization	0.5 - 0.8
IWC	< $2 \times 10^{-4} \text{ g m}^{-3}$

9. ACKNOWLEDGMENTS

The author acknowledges many useful discussions with L. Belsma, W. Cornette, M. Griffin, S. Mazuk, E. Shettle, K. Sassen, and J. Shanks. This work was supported by the U.S. Air Force under contract F04701-88-C-0089, the National Oceanic and Atmospheric Administration's Climate and Global Change Program and the Aerospace Sponsored Research Program

Note added in Proof: Wylie and Menzel⁴⁸ argue that the average global occurrence of thin cirrus may be as high as 75%

10. REFERENCES

1. E. Uthe and P.B. Russell "Lidar Observations of Tropical High Altitude Cirrus Clouds", Proceedings of the IAMAP Symposium on Radiation in the Atmosphere, Garmisch-Partenkirchen, Germany, Science Press, 242-244, 1977
2. A.A. Barnes, "Observations of Ice Particles in Clear Air", J. Rech. Atmos., **14** (3-4), 311-315, 1980
3. A.A. Barnes, "The Cirrus and Sub-Visible Cirrus Background", AFGL-TR-82-0193, Hanscomb AFB, MA, 1982
4. A.J. Heymsfield, "Ice Particles Observed in a Cirriform Cloud at -83 ° C and Implications for Polar Stratospheric Clouds", J. Atmos. Sci., **43**, 851-855, 1986
5. D.J. Rusk, R. Harris-Hobbs and M. Bradford, "Observations of High Altitude Tropical (HAT) Cirrus and Their Implications, Proc. Fourth Airborne Geoscience Workshop, Jan 29 - Feb 1, 1991, La Jolla, 237-240, 1991
6. K. Sassen, M.K. Griffin, and G.C. Dodd, "Optical Scattering and Microphysical Properties of Subvisual Cirrus Clouds, and Climatic Implications" J. Appl. Met., **28**, 91-98, 1989
7. K. Sassen and B.S. Cho, "Subvisual/Thin Cirrus Lidar Dataset for Satellite Verification and Climatological Research" J. Appl. Met., (in press) 1993
8. P.J. Flatau, G.L. Stephens and B.T. Draine "Radiative Properties of Visible and Subvisible Cirrus: Scattering in Hexagonal Ice Crystals", FIRE Science Results 1988 D.S. McDougal, H.S. Wagner, ed., NASA Conf. Publ. 3083, 1990
9. K.N. Liou, Y. Takano, Y., S.C. Ou, A.J. Heymsfield, and W. Kreiss, "Infrared Transmission through Cirrus Clouds: A Radiative Model for Target Detection", Applied Optics, **29**, no. 13, 1 May, 1886-1896, 1990
10. Y. Takano, K.N. Liou, and P. Minnis, "The Effects of Small Ice Crystals on Cirrus Infrared Radiative Properties", J. Atmos. Sci., **49**, 1487-1493, 1992
11. C.M.R. Platt, J.C. Scott, and A.C. Dilley, "Remote Sounding of High Clouds. Part VI: Optical Properties of Midlatitude and Tropical Cirrus", J. Atmos. Sci., **44**, 729-747, 1987
12. K.D. Hutchinsin, J. Mack, R. McDonald, R. and G. Logan, "The Positive Identification of Optically-Thin Cirrus in Nighttime, Multispectral Meteorological Satellite Imagery by Automated Cloud Detection and Typing Algorithms", Proceedings of CIDOS-91, Los Angeles, 1991
13. K.D. Hutchinson, J. Mack, G. Logan, K.R. Hardy, and S. Westerman, "The Identification of Optically-Thin Cirrus Clouds by Automated Classification Algorithms using Nighttime, Multi-Spectral, Multi-Sensor Meteorological Satellite Data", SPIE Conference 1934, Orlando, 1993
14. E.O. Schmidt, J.M. Alvarez, M.A. Vaughn and D.P. Wylie, "A Review of Subvisual Cirrus Morphology", SPIE Conference 1934, Orlando, 1993
15. A. Dalcher, "Cloud-Free Line-Of-Sight (CFLOS) Availability", IDA Document HQ 91-40513, 1992
16. P. Ramos-Johnson, "Thin Cirrus Optical Depth Study", TR-6165-2, The Analytic Science Corporation, Reading, 1992
17. D. Rudy, private communication
18. R.W. Russell and D.K. Lynch, "Lear Jet Based Observations in the Infrared: Final Report", The Aerospace Corp. ATR-88(7164)-1, 1988
19. D.K. Lynch, "Atmospheric Halos," Sci. Am., **238**, 144, 1978
20. P.H. Herzegh and P.V. Hobbs "The Mesoscale and Microscale structure and Organization of Clouds and Precipitation in Mid-latitude Cyclones. II. Warm Frontal Clouds.", J. Atmos. Sci., **37**, 597-611, 1980
21. R. Auria, B. and Campistron, "Origin of Precipitating and Dynamic Organization in Wave-like Precipitation Bands", J. Atmos. Sci., **44**, 3329-3340, 1987
22. K. Sassen, D.O'C. Starr, and T. Uttal, 1989 "Mesoscale and Microscale Structure in

Cirrus Clouds: Three Case Studies, *J. Atmos. Sci.*, **46**, 371-396

23. I.J. Barton, "Upper Level Cloud Climatology from an Orbiting Satellite", *J. Atmos. Sci.*, **40**, 435-447, February, 1983

24. G.E. Woodbury, M.P. McCormick, "Global Distributions of Cirrus Clouds Determined from SAGE Data", *Geophys. Res. Lett.*, **10**, No. 12, 1180-1183, December, 1983

25. G.E. Woodbury, M.P. McCormick, "Zonal and Geographical Distributions of Cirrus Clouds Determined from SAGE Data", *J. Geophys. Res.*, **91**, No. D2, 2775-2785, February 20, 1986

26. E.W. Chiou, M.P. McCormick, W.P. Chu, and G.K. Yue, "Global Distributions of Cirrus Determined from Sage II Occultation Measurements Between Nov. 1984 and Oct. 1988", Paper presented at the Conference on Cloud Physics, American Meteorological Society, San Francisco, July 23-27, 1990

27. A.G. Henderson-Sellers, F. Seze, M. Drake, M. Desbois "Surface-Observed and Satellite-Retrieved Cloudiness Compared for the 1983 ISCCP Special Study Area in Europe", *J. Geophys. Res.*, **92**, No. D4, 4019-4033, April 20, 1987

28. C. Prabhakara, R.S. Fraser, G. Dalu, Man-Li C. Wu, R.J. Curran, and T. Styles, "Thin Cirrus Clouds: Seasonal Distribution over Oceans Deduced from NIMBUS-4 IRIS", *J. Appl. Met.*, **27**, 379-399, 1988

29. W.P. Menzel, D.P. Wylie, "Cloud Cover Determinations with Multispectral VAS Observations: A Two Year Study", *COSPAR: Adv. Space Res.*, **9**, No. 7, 167-173, 1989

30. W.P. Menzel, D.P. Wylie, "Global Semi-Transparent Cloud Statistics from Two Years of HIRS Data", unpublished manuscript, 1992

31. W.B. Rossow and R.A. Schiffer, "ISCCP Cloud Data Products", *B.A.M.S.*, **72**, Number 1, 2-20, January, 1991

32. S.G. Warren, C.J. Hahn, L. London, R.M. Chervin, R.L. Jenne, "Global Distribution of Total Cloud Cover and Cloud Type Amounts Over Land", NCAR Technical Note NCAR/TN-273 + STR, October, 1986

33. S.G. Warren, C.J. Hahn, L. London, R.M. Chervin, R.L. Jenne, "Global Distribution of Total Cloud Cover and Cloud Type Amounts over the Ocean", NCAR Technical Note NCAR/TN-317 + STR, December, 1988

34. D.P. Wylie and W.P. Menzel, "Two years of Cloud Cover Statistics Using VAS", *J. Climate*, **2**, 380-392, April, 1989

35. D.P. Wylie, "Cloud Cover Statistics", Geophysics Laboratory Technical Report GL-TR-90-0146, May, 1990

36. D.R. Dowling and L.F. and Radke, L.F., "A Summary of the Physical Properties of Cirrus Clouds", *J. Appl. Met.*, **29**, 970-978, September, 1990

37. A.J. Heymsfield and C.M.R. Platt, "A parameterization of the Particle Size Spectrum of Ice Clouds in Terms of the Ambient Temperature and Ice Water Content", *J. Appl. Met.*, **41**, 846-855, 1984

38. C.M.R. Platt and J.D. Spinhirne, "Optical and Microphysical Properties of a Cold Cirrus Cloud: Evidence for Regions of Small Ice Particles", *J. Geophys. Res.*, **94**, no. D8, 11151-11164, 1989

39. E.P. Shettle, F.X. Kneizys, S.A. Clough, G.P. Anderson, I.W. Abreu, and J.H. Chetwynd, "Cloud Models in LOWTRAN and FASCOD", *Proceedings of CIDOS-88*, 199-206, 1988

40. E.P. Shettle, "Models of Aerosols, Clouds and Precipitation for Atmospheric Propagation Studies", *Proceedings of NATO/AGARD meeting Atmospheric Propagation in the UV, Visible, IR and mm-Wave Region and Related Systems Aspects*, Copenhagen, 9-13 October, 1989

41. K. Sassen, "The Polarization Lidar Technique for Cloud Research: A Review and Current Assessment", *B.A.M.S.*, **72**, No. 12, December, 1991

42. S. Ackerman, W.A. Smith, J.D. Spinhirne and H.E. Revercomb, "Remote Sounding Through Semi-Transparent Cirrus Clouds", *Mon. Wea. Rev.*, **118**, 2377-2388, 1989

43. A.J. Palmer, S.Y. Matrosov, B.E. Martner, T. Uttal, D.K. Lynch, M.A. Chatelain,

R.W. , Russell, and J.A. Hackwell, 1993 "Combined Infrared Emission Spectra and Radar Reflectivity Studies of Cirrus Clouds", IEEE Trans. Geo. Sci. and Rem. Sens. (in press) 1993

44. D.K. Lynch "On Using the 9.6 μm Ozone Emission Band for Passive Remote Sensing of Tropospheric Clouds." Geophys. Res. Let.(submitted) 1993

45. S. Matrosov, D.K. Lynch, and J. Churnside, "Possibilities of Using IR Spectrometer data for Sizing Cirrus Cloud Particles" SPIE Conference 1934, Orlando, 1993

46. R.P. d'Entremont, M.K. Griffin, and J.T. Bunting, J.T., "Retrieval of Cirrus Radiative Properties and Altitudes Using Multispectral Infrared Data", Fifth Conference on Satellite Meteorology and Oceanography, London, Amer. Met. Soc., 4-9, 1990

47. R.W. Saunders, R.W. and K.T. Kreibel, "An Improved Method for Detecting Clear Sky and Cloudy Radiances from AVHRR", Int. J. Rem. Sens., 9, no. 1, 123-150, 1988

48. Wylie, D.P. and Menzel, W.P., "Trends in Global Cirrus Inferred from three years of HIRS Data", SPIE Conference 1934, Orlando, 1993

TECHNOLOGY OPERATIONS

The Aerospace Corporation functions as an "architect-engineer" for national security programs, specializing in advanced military space systems. The Corporation's Technology Operations supports the effective and timely development and operation of national security systems through scientific research and the application of advanced technology. Vital to the success of the Corporation is the technical staff's wide-ranging expertise and its ability to stay abreast of new technological developments and program support issues associated with rapidly evolving space systems. Contributing capabilities are provided by these individual Technology Centers:

Electronics Technology Center: Microelectronics, solid-state device physics, VLSI reliability, compound semiconductors, radiation hardening, data storage technologies, infrared detector devices and testing; electro-optics, quantum electronics, solid-state lasers, optical propagation and communications; cw and pulsed chemical laser development, optical resonators, beam control, atmospheric propagation, and laser effects and countermeasures; atomic frequency standards, applied laser spectroscopy, laser chemistry, laser optoelectronics, phase conjugation and coherent imaging, solar cell physics, battery electrochemistry, battery testing and evaluation.

Mechanics and Materials Technology Center: Evaluation and characterization of new materials: metals, alloys, ceramics, polymers and their composites, and new forms of carbon; development and analysis of thin films and deposition techniques; nondestructive evaluation, component failure analysis and reliability; fracture mechanics and stress corrosion; development and evaluation of hardened components; analysis and evaluation of materials at cryogenic and elevated temperatures; launch vehicle and reentry fluid mechanics, heat transfer and flight dynamics; chemical and electric propulsion; spacecraft structural mechanics, spacecraft survivability and vulnerability assessment; contamination, thermal and structural control; high temperature thermomechanics, gas kinetics and radiation; lubrication and surface phenomena.

Space and Environment Technology Center: Magnetospheric, auroral and cosmic ray physics, wave-particle interactions, magnetospheric plasma waves; atmospheric and ionospheric physics, density and composition of the upper atmosphere, remote sensing using atmospheric radiation; solar physics, infrared astronomy, infrared signature analysis; effects of solar activity, magnetic storms and nuclear explosions on the earth's atmosphere, ionosphere and magnetosphere; effects of electromagnetic and particulate radiations on space systems; space instrumentation; propellant chemistry, chemical dynamics, environmental chemistry, trace detection; atmospheric chemical reactions, atmospheric optics, light scattering, state-specific chemical reactions and radiative signatures of missile plumes, and sensor out-of-field-of-view rejection.